The X,Y,Z states from lattice QCD: progress and prospects

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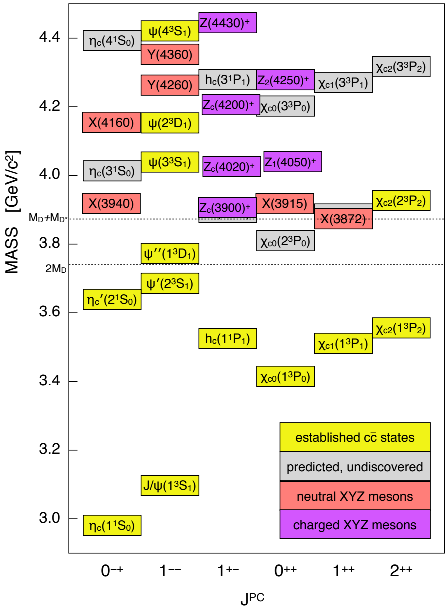
Outline

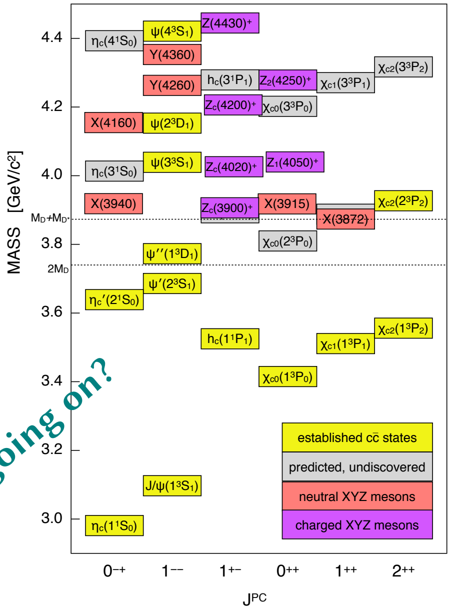
- Introduction and motivation
- Benchmark calculations - do we get the right answers?
- Making predictions and understanding new puzzles
  - going beyond ground state spectroscopy
  - going beyond bound states to resonances and scattering states and the XYZs
- Recent and very recent results
- Lattice and experimental prospects. A role for the EIC?

Motivation - a charm revolution



S. Olsen Bormio2015, 1511.01589

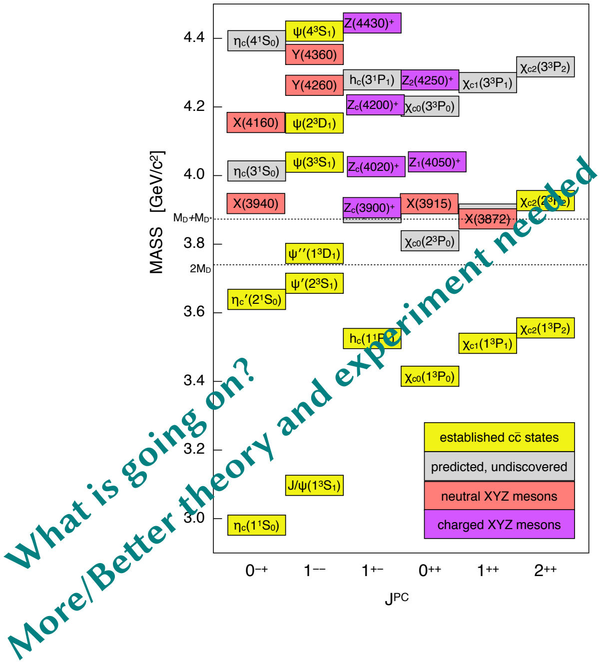
MOTIVATION - A CHARM REVOLUTION



What is going on?

S. Olsen Bormio2015, 1511.01589

Motivation - a charm revolution



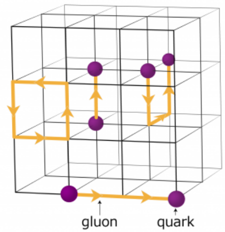
S. Olsen Bormio2015, 1511.01589

A lattice QCD primer

Start from the QCD Lagrangian:

$$\mathcal{L} = \bar{\Psi}\left(i\gamma^{\mu}D_{\mu} - m\right)\Psi - \frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}$$

Gluon fields on links of a hypercube;
Quark fields on sites: approaches to fermion discretisation - Wilson, Staggered, Overlap.;
Derivatives → finite differences.



Solve the QCD path integral on a finite lattice with spacing $a \neq 0$ estimated stochastically by Monte Carlo. Can only be done effectively in a Euclidean space-time metric (no useful importance sampling weight for the theory in Minkowski space).

Observables determined from (Euclidean) path integrals of the QCD action

$$\langle \mathcal{O} \rangle = 1/Z \int \mathcal{D}U\mathcal{D}\bar{\Psi}\mathcal{D}\Psi \; \mathcal{O}[U, \bar{\Psi}, \Psi] e^{-S[U,\bar{\Psi},\Psi]}$$

A RECIPE FOR (MESON) SPECTROSCOPY

- Construct a basis of local and non-local operators $\bar{\Psi}(x)\Gamma D_i D_j \ldots \Psi(x)$ from *distilled* fields [PRD80 (2009) 054506].
- Build a correlation matrix of two-point functions

$$C_{ij} = \langle 0|\mathcal{O}_i \mathcal{O}_j^\dagger|0\rangle = \sum_n \frac{Z_i^n Z_j^{n\dagger}}{2E_n} e^{-E_n t}$$

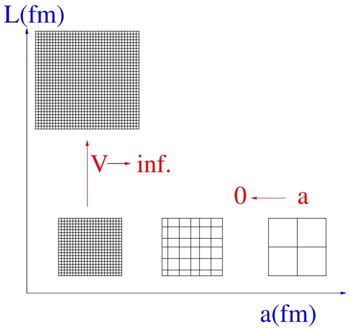
- Ground state mass from fits to $e^{-E_n t}$
- Beyond ground state: Solve generalised eigenvalue problem $C_{ij}(t) v_j^{(n)} = \lambda^{(n)}(t) C_{ij}(t_0) v_j^{(n)}$

- eigenvalues: $\lambda^{(n)}(t) \sim e^{-E_n t}\left[1 + O(e^{-\Delta E t})\right]$ - principal correlator
- eigenvectors: related to overlaps $Z_i^{(n)} = \sqrt{2E_n} e^{E_n t_0/2} v_j^{(n)\dagger} C_{ji}(t_0)$

Some Compromises and their Consequences

for spectroscopy

1. Working in a finite box at finite grid spacing



- Identify a "scaling window" where physics doesn't change with a or V. Recover continuum **QCD** by extrapolation.

A costly procedure but a regular feature in lattice calculations now

2. Simulating at physical quark masses

- Computational cost grows rapidly with decreasing quark mass $\rightarrow m_q = m_{u,d}$ costly. Care needed vis location of decay thresholds and identification of resonances.
- Heavy quarks: c-quark relativistically; b-quark with EFTs.

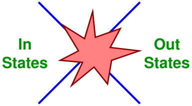
Physical light quark simulations possible. Heavy quark systematics understood.

Use lattice simulations to study *quark mass dependence*!

2. Breaking symmetry

- Lorentz symmetry broken at $a \neq 0$ so $SO(4)$ rotation group broken to discrete rotation group of a hypercube.

Spin identification at finite lattice spacing: 0707.4162, 1204.5425



3. Working in Euclidean time.

- Scattering matrix elements not directly accessible from Euclidean QFT [*Maiani-Testa theorem*].

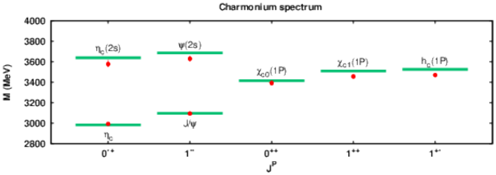
Lüscher and generalisations of method for indirect access.

Benchmark Spectroscopy:
states below strong decay thresholds

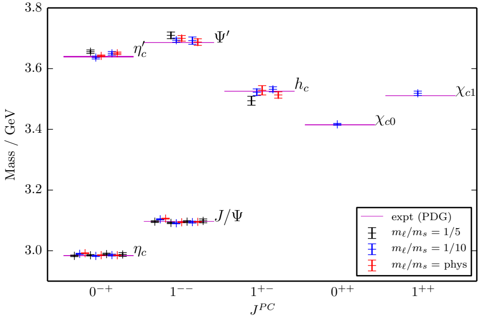
CHARMONIUM BELOW THRESHOLD - "GOLD-PLATED"

- $N_f = 2, 2+1, 2+1+1$
- Different actions in agreement. High statistics and improved actions.
- Simulation at m_q^{phys} or extrapolation $m_q \rightarrow m_q^{\text{phys}}$.
- Discretisation errors $\mathcal{O}(am_c)$ and $\mathcal{O}(am_b)$ under control.

Perez-Rubio, Collins, Bali 1503.08440



Charmonium, HPQCD 1411.1318



No disconnected diagrams: OZI suppressed - assumed to be small
$\Rightarrow$ mixing with lighter states not included. Kicking this can of worms down the road!

Beyon benchmark spectroscopy:
excited and exotic states

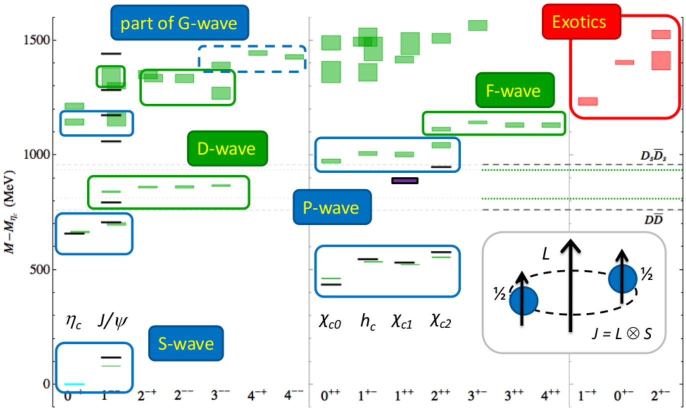
Single hadron states: above threshold

Precision calculation of high spin ($J \geq 2$) and exotic states is relatively new

Caveat Emptor

- Only single-hadron operators
- Physics of multi-hadron states appears to need relevant operators
- No continuum extrapolation
- $M_\pi \sim 400\text{MeV}$. With $M_\pi = 230\text{MeV}$ arXiv:1610.01073 no change to pattern of states

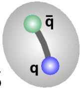
Charmonium

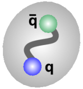


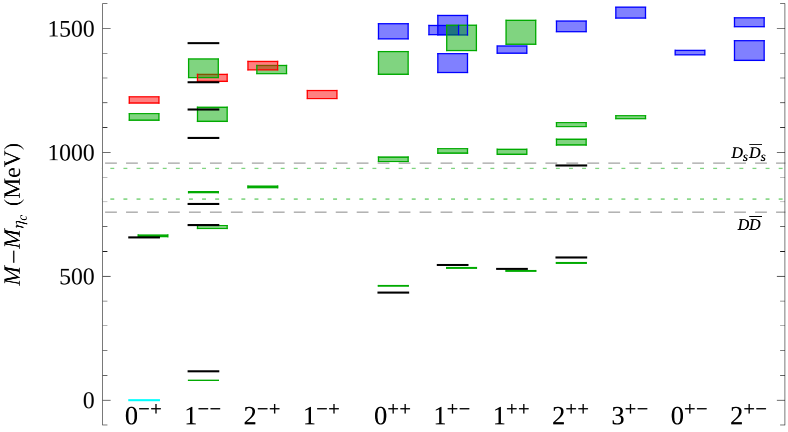
Hadron Spectrum Collab. 2012

→ Expect improvements now methods established

Hybrids







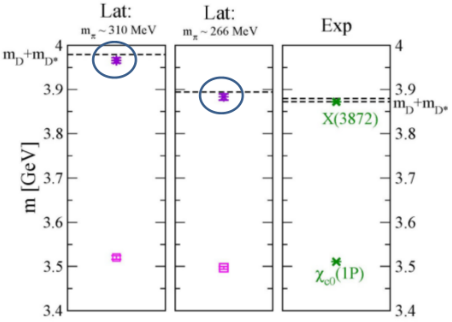
Charmonium hybrids from HSC 2012

- Lightest hybrid supermultiplet and excited hybrid supermultiplet. Includes **exotic** $J^{PC} = 1^{-+}, 0^{+-}, 2^{+-}$.
- Exotic J^{PC} not accessible in e^+e^- but could be studied in photoproduction (EIC?) and in $p\bar{p}$ annihiliation (PANDA@GSI).

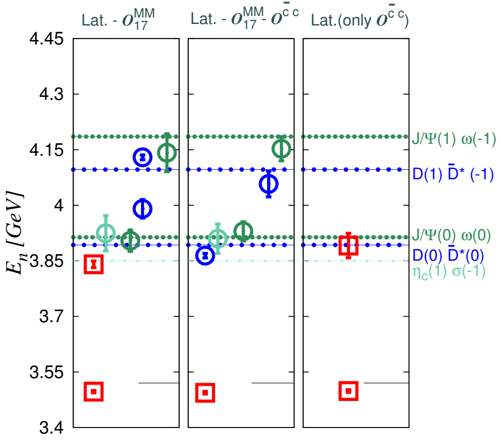
Spectroscopy above decay thresholds
some examples from the XYZs

X(3872) - a first look (no coupled channels)

Prelovsek & Leskovec 1307.5172



Padmanath, Lang, Prelovsek 1503.03257



ground state: $\chi_{c1}(1P)$
$D\bar{D}^*$ scattering mx: pole just below thr.
Location of thr., finite vol effects controlled?

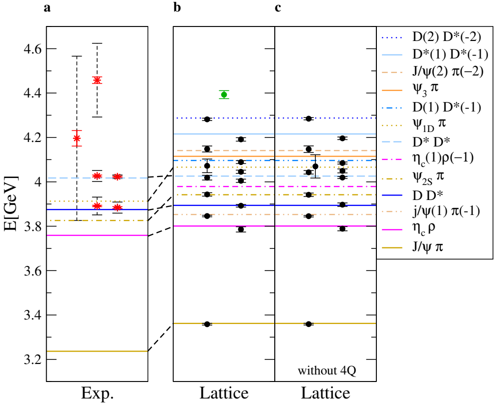
X(3872) not found if $c\bar{c}$ not in basis.

Also results from Lee et al 1411.1389

Within 1MeV of $D^0\bar{D}^{0*}$ and 8MeV of D^+D^* thresholds: isospin breaking effects important?

Z_c^+ - First look on the lattice (no coupled channels)

Manifestly exotic hadron i.e. does not fit in the quark model picture.



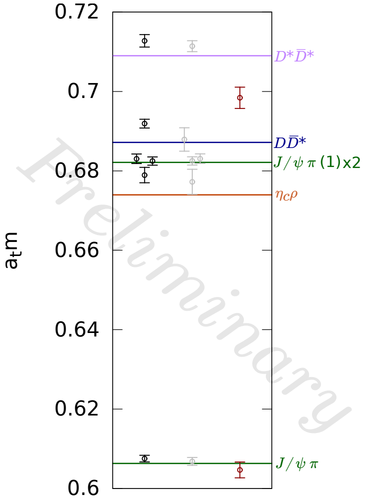
Prelovsek, Lang, Leskovec, Mohler: 1405.7615

- 13 expected 2-meson e'states found (black)
- no additional state below 4.2GeV
- no Z_c^+ candidate below 4.2GeV

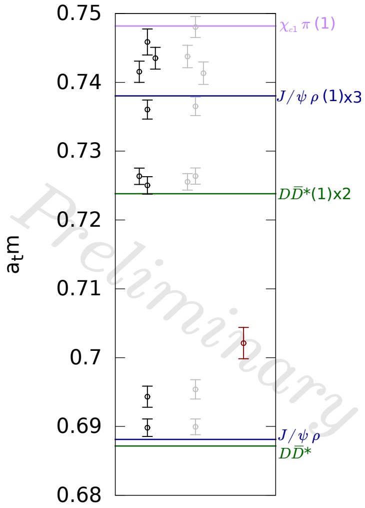
Similar conclusion from Lee et al [1411.1389] and Chen et al [1403.1318]

Why no eigenstate for Z_c? Is Z_c^+ a coupled channel effect? Work needed!

Recent (preliminary) work - charm tetraquarks



only tetraquark ops
only meson-meson ops
full basis of ops
from G.Cheung, HadSpec



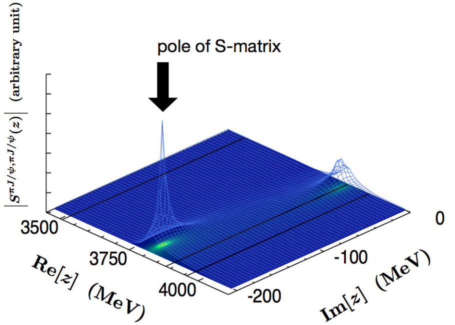
$I^G(J^{PC}) = 1^+(1^{+-})$: No candidate state for Z_c^+ found.

Charged $X(3872)$ in $I = 1$, $\bar{c}c\bar{d}u$? No candidate state seen. **BUT** Isospin breaking and unstable ρ not included.

Other recent work: Z_c^+

A coupled-channel analysis by HAL QCD[1602.03465].

$\pi J/\Psi - \rho\eta_c - \bar{D}D^*$



Challenges:

- The Z_c^+ (as other XYZ states) lies above several thresholds and so decays to several two-meson final states
- Requires a coupled-channel analysis for a rigorous treatment
- On lattice the number of relevant coupled-channels is large for high energies.

- Potential method, not robustly tested.
- Suggest Z_c^+ a threshold cusp.

Other lattice results are needed to test this result

PROSPECTS FOR CHARMONIUM PHYSICS

- There have been many “first looks” at exotic, XYZ charmonium states in 2012-2015.
- The existing framework for two coupled channel analysis provides a path forward to study these states in more realistic scenarios.
- The first coupled channel study with charm quarks, by HadSpec, described in JHEP 1610 (2016) 011. Similar studies for $c\bar{c}$ planned.
- Charmonium radiative transitions also underway. Note resonant amplitudes also now studied: $\pi^+\gamma \to \rho \to \pi^+\pi^0$ in [Briceño et al, HadSpec 1604.03530].
- Studies of $X(5568)$ in $B_s\pi$ [PRD 94 (2016) 074509] and revisiting pentaquarks underway [Prelovsek et al].

Challenges remain

- technical challenges remain - memory requirements!
- Proliferation of coupled channels in charmonium
- Reducing pion mass - more channels ... going beyond two coupled channels remains a practical challenge

Understanding this extended charming family

Charmonium a beautiful arena to probe the strong interaction by studying XYZs

- Theory: Improving lattice calculations - underway!
- Experiment: current and near-future
  - e^+e^- : CLEO, BELLE II, BaBar, BESIII ; pp : LHCb

  and medium-future
  - $p\bar{p}$: PANDA @ GSI ; Photoproduction: GlueX, ..., **EIC?**

What can EIC do?

- Photoproduction provides new avenues to explore XYZ states - complementary to current picture. Several proposals for XYZs in photoproduction
  - $\gamma p \to Z_c^+(4430)n,\ Z_c^+ \to \Psi'\pi^+$ PRD77 (2008) 094005
  - $\gamma p \to Z_c^+(3900)n,\ Z_c^+ \to J/\Psi\pi^+$ PRD 88 (2013) 114009
  - $\gamma p \to Z_c^+(4200)n,\ Z_c^+ \to J/\Psi\pi^+$ PRD 92 (2015) 094017
  - $\gamma p \to Y(3940)p,\ Y \to J/\Psi\omega$ PRD 80 (2009) 114007
- Hybrids - exotic J^{PC} not accessible in e^+e^- but could be studied in photoproduction (EIC?) and in $p\bar{p}$ annihiliation (PANDA@GSI).

Lots of exciting physics opportunities!